STIMULATED BRILLOUIN SCATTERING IN MULTISPECIES PLASMAS

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Introduction

Stimulated Brillouin scattering (SBS) is a plasma instability in which laser light, propagating through an underdense plasma, is scattered by self-excited ion-acoustic waves.[1]

In inertial confinement fusion (ICF) applications, backscattered laser light is wasted energy that is not absorbed by the target. It is neither converted to x rays by the laser-heated hohlraum (indirect drive) nor used to directly implode the target (direct drive). Energy lost in this manner has to be replaced by a compensating increase in the power of the laser.

Scattering in directions other than backward, or near backward, gives rise to a different concern. This obliquely scattered light may be absorbed elsewhere in the hohlraum, or by the capsule, changing the spatial distribution of absorbed energy and affecting implosion symmetry. Although scattering adds to the effective "spot motion" it can, within limits, be tuned away in the target design. The real concern is that the shot-to-shot variation of the scattering might exceed the tolerance of the design.[2–4]

Because of this consideration, it would be highly desirable to limit SBS scattering to not more than a few percent of the incident power. Limiting laser intensity and the hohlraum gas density, for instance, are possibilities. In this article, we discuss the possible benefits of choosing hohlraum gases[5] and / or hohlraum wall materials[6] that contain multiple-ion species to increase the ion Landau damping of the SBS ion waves.

Under cryogenic constraints, the only candidate for a mixed species gas is a hydrogen–helium (H–He) mixture, currently used in the National Ignition Facility (NIF) designs.[2,3] Gases such as methane, propane, pentane, and carbon dioxide[7] have been used in Nova hohlraum and gas-bag experiments. Recent Nova experiments have used Au hohlraums with multilayers of Au and Be to coat the inside walls.

Landau Damping of Ion-Acoustic Waves

Theoretically, increasing the linear damping rate of the SBS ion waves, all else equal, should reduce the amplitude to which they grow, and consequently reduce the amount of scattered light. If the reduction of linear growth rate is sufficient to force the instability to remain in a linear regime, there is a quantitative relation between growth rate and reflectivity. Conversely, if the relevant rates are reduced, but the ion waves are nevertheless driven nonlinear, then the connection between increased damping and reduced scatter is less direct. A connection is anticipated, however, and is the subject of current research.

To our benefit, nature provides the natural phenomenon of (ion) Landau damping. This is a kinetic (as opposed to fluid) effect, in which ions in the distribution function whose (thermal) velocities match the phase speed of the ion acoustic wave, "surf" on the wave, thereby extracting energy and damping it. More precisely, ions slightly slower than the wave are accelerated, those slightly faster are decelerated. Because, in a thermal distribution, the number of ions decreases with increasing velocity (i.e., the distribution function has negative slope), the net effect is damping.

When the ion acoustic velocity greatly exceeds the characteristic thermal velocity, the number of ions available on the tail of the distribution is very small, and the damping is weak. In the opposite limit, where the ion thermal velocity greatly exceeds the acoustic velocity, the damping is again weak because the distribution function is locally almost flat. Maximum damping occurs in the intermediate case where the ion acoustic velocity is two to three times the thermal velocity. Because, at a given ion temperature, the ion thermal velocity varies inversely with the square root of the atomic mass, the ion Landau damping can be controlled by judicious choice of material composition.

In a single-ion-species underdense plasma, the ratio of the ion acoustic speed to the ion thermal velocity $\left(ZT_e / T_i\right)^{1/2}$ is large for both mid- and high-Z plasmas, both because Z>>1 and because electron-ion collisions are insufficient for the ion temperature T_i to equilibrate with the laser-heated electrons, where T_e is the electron temperature. In Nova hohlraums, $T_i / T_e \approx 0.2$; for the longer pulse lengths in NIF hohlraums, we anticipate $T_i / T_e \approx 0.5$. Because of this, the fraction of ions in such a plasma near the phase velocity of the ion wave is very small, making ion Landau damping very weak.

Typically, adding a low atomic number component, such as H, to a plasma modestly changes the ion acoustic frequency, but greatly increases the number of high-thermal-velocity ions, thereby dramatically increasing the Landau damping. This multispecies effect was first examined in the early days of magnetic fusion research and was experimentally tested in a variety of experiments,[8] including an observation of reduced SBS in a microwave plasma.[9] This work has been extended to consider plasmas of interest to ICF[5] and is summarized here.

We consider the kinetic treatment of ion acoustic waves in a plasma, consisting of an arbitrary number of ion species. We assume Maxwellian velocity distributions, with common ion temperature T_i and electron temperature T_e. The electrostatic normal-mode frequencies of the plasma are then given by the zeroes of the plasma dielectric function ε, which relates the frequency ω to the wavenumber k, of any given mode, written as follows:

$$\varepsilon(k,\omega) = 1 + \chi_e + \sum_\beta \chi_{i\beta} = 0 \ , \tag{1}$$

where the electron susceptibility is χ_e and the ion susceptibility for species β is $\chi_{i\beta}$. The susceptibilities can be expressed as derivatives of Fried and Conte's Z function[10]

$$\chi_e = -\frac{\omega_{pe}^2}{2k^2 v_e^2} Z'\left(\frac{\omega}{\sqrt{2}k v_e}\right)$$

and

$$\chi_{i\beta} = -\frac{\omega_{pi\beta}^2}{2k^2 v_{i\beta}^2} Z'\left(\frac{\omega}{\sqrt{2}k v_{i\beta}}\right), \tag{2}$$

in which the plasma frequency and thermal speed are ω_{pe} and v_e for the electrons and $\omega_{pi\beta}$ and $v_{i\beta}$ for the ion species. The thermal speed of species β is defined here by $v_\beta = \sqrt{T_\beta / A_\beta M_p}$ (consistent with the practice in the laser–plasma literature but in contrast, for example, to Swanson[10]), where M_p is the proton mass, and T_β and A_β are the temperature, in energy units, and the atomic mass of species β. We ignore flow. If the component species were to all flow with velocity u, ω would be replaced in all of the above by $(\omega - \mathbf{k} \cdot \mathbf{u})$.

The theoretical discussion is more straightforward if we convert to normalized units: $K \equiv k\lambda_{De}$, $\Omega = \omega/\omega_{pe}$, and $V_\beta = v_\beta/v_e$, with electron Debye length $\lambda_{De} \equiv v_e/\omega_{pe}$. We take the ionic charge and the number fraction of the β species to be Z_β and f_β. The total ion density n_i and the electron density n_e are related through the average charge $\overline{Z}$, as $n_e = n_i\overline{Z}$. The average charge and ion number densities are then related by

$$\overline{Z} \equiv \sum_\beta f_\beta Z_\beta \ \text{ and } \ n_\beta = f_\beta n_e / \overline{Z} = f_\beta n_i \quad . \tag{3}$$

In these units,

$$\chi_e = -Z'\left(\Omega / \sqrt{2}K\right) / 2K^2$$

and

$$\chi_{i\beta} = \frac{f_\beta Z_\beta^2}{\overline{Z}} \frac{T_e}{T_i} \frac{1}{2K^2} Z'\left(\Omega / \sqrt{2}K V_\beta\right) \quad . \tag{4}$$

Although this dispersion relation has an infinite number of roots, $\omega(k)$, only a small number of them have $\omega_i << \omega_r$, corresponding to freely propagating waves (where i and r denote the imaginary and real parts of the complex mode frequency). For these, their phase velocity $\mathrm{Re}(\omega) / k$ is such that it is either much larger than or much less than the thermal velocity of each species. The Landau damping contribution of each species is then small because the number of particles at the phase velocity, or the slope of the particle distribution function, is small.

For high enough electron temperature [approximately when $T_e / T_i > 3\langle Z\rangle / \left(\langle Z^2 / A\rangle A_1\right)$], there is a "fast" ion acoustic wave that is weakly damped. The $\langle \ \rangle$ denote averages weighted by the ion fractions. A_1 is the atomic number of the lightest component. The condition implies that the sound speed is much greater than the thermal velocity of the lightest ion species. The sound speed is approximated by

$$\left(\frac{\Omega_r}{K}\right)^2 = \frac{m_e}{M_p}\left(\frac{\langle Z^2 / A\rangle}{\overline{Z}(1+K^2)} + \frac{\langle Z^2 / A^2\rangle}{\langle Z^2 / A\rangle}\frac{3T_i}{T_e}\right) \quad , \tag{5}$$

where m_e is the electron mass.

In un-normalized quantities,

$$\left(\frac{\omega_r}{k}\right)^2 = \frac{\langle Z^2 / A\rangle T_e / \overline{Z} M_p}{1+k^2\lambda_{De}^2} + \frac{\langle Z^2 / A^2\rangle}{\langle Z^2 / A\rangle}\frac{3T_i}{M_p} \ . \tag{6}$$

The sound speed is of course much slower than the electron thermal velocity. The electron damping puts a lower limit on the total ion wave damping, which is approximately given by

$$\frac{\Omega_i}{\Omega_r} = -\sqrt{\frac{\pi}{8}}\frac{1}{1+\mu+K^2}\left(\frac{\Omega_r}{K} + \sum_\beta \frac{\alpha_\beta \Omega_r}{K V_\beta} e^{-\Omega^2 / 2K^2 V_\beta^2}\right), \tag{7}$$

which gives a minimum damping decrement of 0.01–0.015 in cases of interest.

The "fast" mode is the direct analog of the usual single-species ion wave. However, in a multi-ion species plasma there are possibilities for additional "slow" modes. These modes have sound speeds intermediate between the thermal velocities of a light group of ion species and a heavy group. In these modes, the light ions act like the electrons in the fast mode. They, together with the electrons, react so as to charge–neutralize the heavy ions. Unlike the electrons, the light ions are repelled by the regions of heavy-ion concentration. Their motion is thus out of phase with the heavy ions. This contrasts with the fast mode where the electron and ion species motions are in phase, so that the plasma is effectively a single fluid.

A weakly damped fast mode always exists for sufficiently large T_e / T_i, whereas slow modes exist for at most a finite range of T_e / T_i. Detailed criteria for the existence of these modes have been published elsewhere.[12] Asymptotic kinetic and multifluid approximations for the frequency and damping decrement of the slow modes are readily derived, but are only modestly quantitatively accurate, essentially because the ratios of the sound speed to the ion thermal velocities are neither particularly large nor small.

Figures 1 and 2 show the sound speed and damping decrement as a function of T_i / T_e for equal mixtures of H with He and C—mixtures of interest for the NIF and current Nova experiments. In each case, there are fast and slow modes. The fast mode is less damped when T_i / T_e is <0.2 or 0.32, respectively, with the slow mode becoming the lesser damped mode at higher values of T_i / T_e. One consequence of this is that the sound speed of the dominant mode increases less rapidly with T_i than would be anticipated from the fluid result [see Eqs. (5) and (6)].

Also shown in Figs. 1 and 2 are the thermal velocities of the two ion species, which can be compared with the respective sound velocities. In contrast with the CH mixture, the H thermal velocity in the H–He mixture does not actually exceed the slow mode phase speed. Because of this, the ion acoustic damping for H–He mixtures is very strong at the T_i / T_e ratios anticipated for NIF hohlraums (~0.5).

SBS in Multispecies Plasmas

The kinetic dispersion relation for SBS is

$$\frac{1+\chi_e+\sum_i \chi_i}{\left[\chi_e\left(1+\sum_i \chi_i\right)\right]}\left[(\omega_0-\omega)^2-\omega_{pe}^2-(k_0-k)^2\right]=\frac{k^2 v_0^2}{4}. \quad (8)$$

The frequency and wave number of the pump and ion wave are (ω_0, k_0) and (ω, k), respectively. The simplest linear model to assess the effect of ion acoustic damping on SBS is to take the plasma to be a homogeneous slab and the laser beam to be uniform. The time development of the SBS instability in such a model has been analyzed in detail.[13] The instability grows as if the

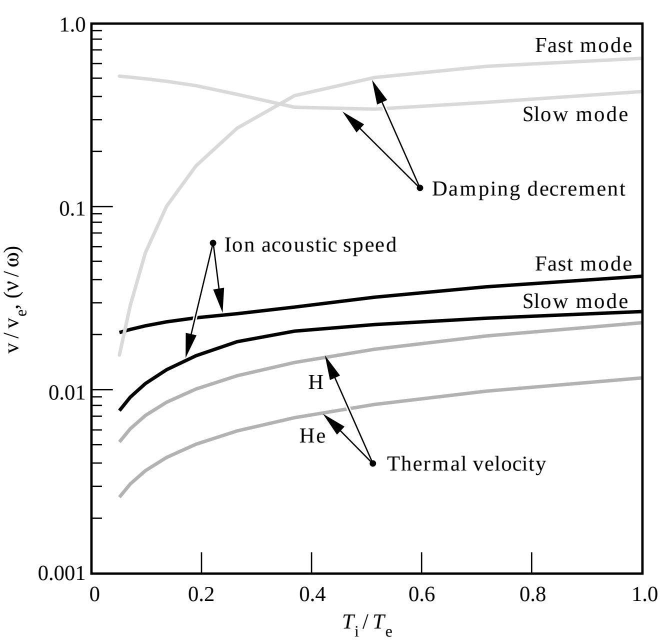

FIGURE 1. A plot of the damping decrement ν/ω and the ion-acoustic and thermal velocities normalized to the electron thermal velocity vs the ion-electron temperature ratio T_i / T_e. The H–He plasma has T_e = 3 keV and $n_e = 10^{21}$ cm^{-3}. (50-01-1195-2518pb01)

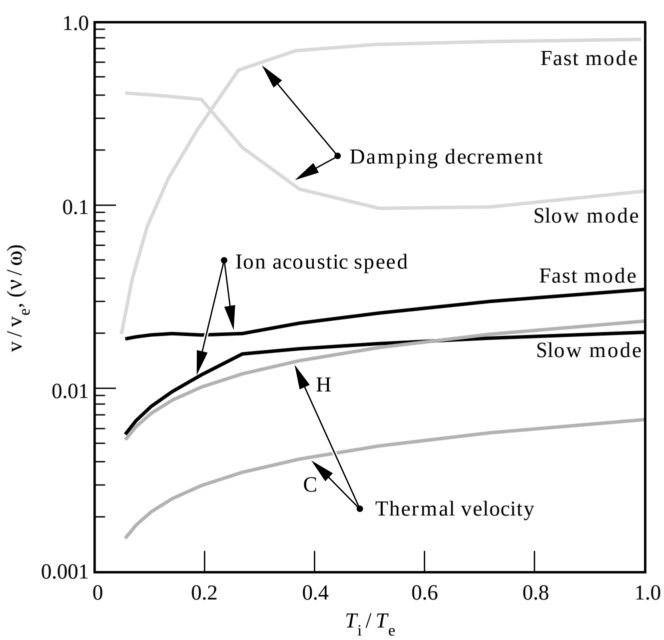

FIGURE 2. A plot of the damping decrement ν/ω and the ion acoustic and thermal velocities normalized to the electron thermal velocity vs the ion-electron temperature ratio T_i / T_e. The CH plasma has T_e = 3 keV and $n_e = 10^{21}$ cm^{-3}. (50-01-1195-2519pb01)

medium were infinite for the first few light transit times. The appropriate growth rate is given by the root of Eq. (8) for complex ω maximized over (real) *k*.

In a reduced mode-coupling description, this temporal growth rate is given by

$$\gamma = -\nu/2 + \left[\gamma_0^2 + (\nu/2)^2\right]^{1/2} \quad (9)$$

where γ_0 is the growth rate in the absence of damping, and ν is the ion-acoustic damping rate. One therefore anticipates that the initial growth rate is unaffected by damping whenever $\gamma_0 \gg \nu$. This result is borne out by solutions of the full kinetic dispersion relation [see Eq. (8)]. Unless the intensity is relatively low (less than ~10^{14} W/cm^2) and the damping is high (decrement >0.1), the kinetic temporal growth rate is essentially independent of material composition.

However, provided the damping is strong enough to prevent absolute instability, which in the mode-coupling model requires $\gamma_0 < (\nu/2)(c/c_s)^{1/2}$, where c_s is the sound speed, the instability evolves into a steady state in which the scattered wave amplifies exponentially from noise across the plasma. The spatial growth rate is given by the imaginary part of the solution of the dispersion relation [see Eq. (8)] for (complex) *k*, maximized over the frequency shift ω.

Below the absolute threshold, it is a good approximation to neglect the imaginary part of *k* in evaluating the susceptibilities, giving the following expression for the spatial growth rate:

$$\kappa = \frac{k^2 v_0^2}{4c^2} \frac{\left|1 + \sum_i \chi_i\right|^2 \mathrm{Im}(\chi_e) + |\chi_e|^2 \mathrm{Im}\left(\sum_i \chi_i\right)}{\left|1 + \chi_e + \sum_i \chi_i\right|^2} \quad , \quad (10)$$

which is directly proportional to the Thomson cross section.

It might be expected that whenever two weakly damped ion acoustic waves are present, the SBS (and Thomson) spectra would exhibit two peaks. In fact, except for special choices of material and electron-ion temperature ratio, a single peak is observed. This is because it is not easy to satisfy the Rayleigh criterion that the separation of the peaks has to exceed their combined widths.

Figure 3 shows the spatial amplification rate for backward SBS from a 10^{15} W/cm^2, 0.35-μm laser in a fully-ionized CH plasma, with T_e = 3 keV and $n_e = 10^{21}$ cm^{-3}, plotted against the wavelength shift of the scattered light in Angstroms. Curve A in Fig. 3 shows $T_i/T_e = 0.075$. At this temperature, in comparison with Fig. 2, the fast mode is weakly damped and the slow mode is nonresonant. The growth rate curve shows a sharp peak, with a shift corresponding to the fast wave ion-acoustic frequency. Curve B shows $T_i/T_e = 0.2$, where both modes are modestly (and equally) damped, but only a single broad peak is seen in the spectrum, with an inferred ion-acoustic velocity between that of the two ion modes. In curves C and D where T_i/T_e increases, the peak shifts and narrows, reflecting a contribution only from the slow mode.

Figure 4 plots the spatial growth rate (maximized over scattered frequency) for SBS backscatter vs T_i/T_e

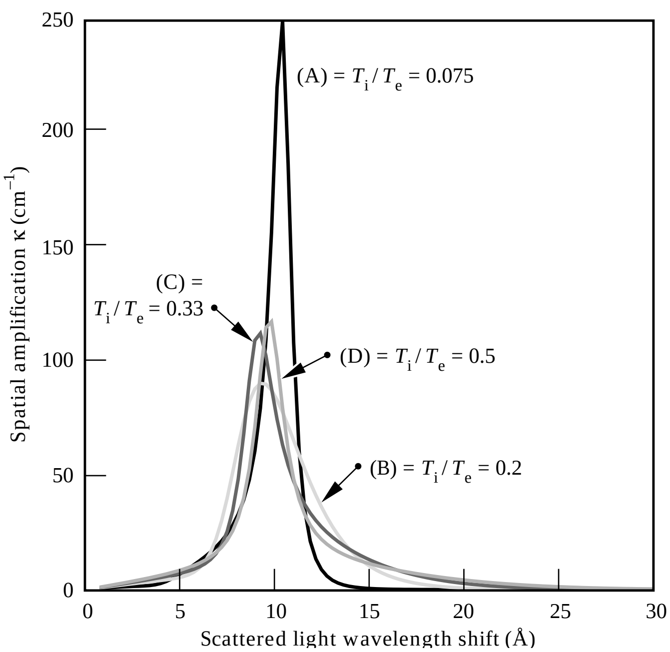

FIGURE 3. A plot of the SBS backscatter spatial amplification rate in a CH plasma vs the wavelength shift of the scattered light. The 0.35-μm $I_L = 10^{15}$ W/cm^2, and the plasma has T_e = 3 keV and $n_e = 10^{21}$ cm^{-3}. (50-01-1195-2520pb01)

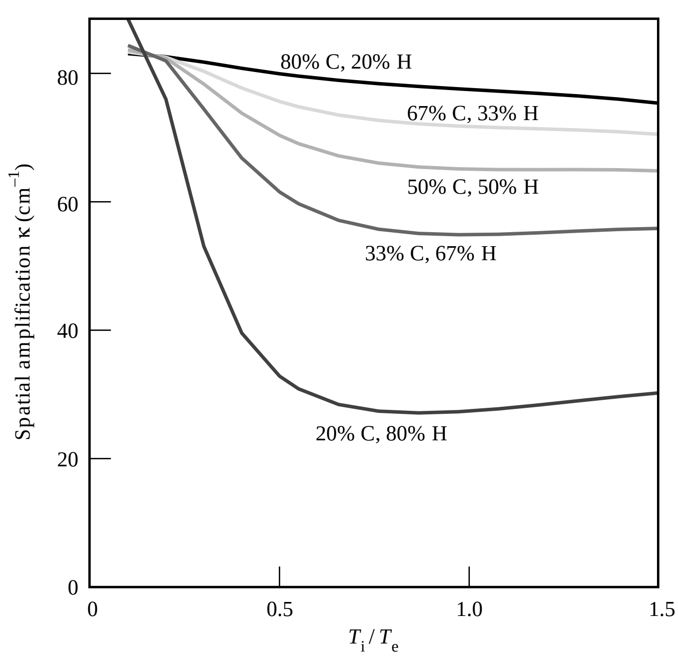

FIGURE 4. A plot of the maximum (over wavelength) SBS backscatter spatial amplification rate vs T_i/T_e for various CH mixtures for the conditions of Fig (3). (50-01-1195-2521pb01)

for various C–H mixtures. Here, adding increasing fractions of light H ions to the C plasma decreases the spatial amplification rate for SBS. In these calculations, the laser intensity $I_L = 10^{14}$ W / cm^2, T_e = 3 keV, and $n_e = 10^{21}$cm^{-3}. Below the absolute threshold, the kinetic growth rates scale as its fluid approximation, namely as $I_L n_e / T_e$, keeping the material variation intact.

Conclusion

The Landau damping of ion-acoustic waves can be substantially higher in plasmas that contain mixtures of ionic species than that encountered in single-species plasmas. In multispecies plasmas, the linear spatial growth rate of stimulated Brillouin scattering is substantially reduced. Despite the big gap between linear models of SBS in a uniform plasma and the realities of nonlinear saturation, structured laser beams, and nonuniform plasmas, the simplicity of the physics suggests that the tailoring of material compositions to maximize Landau damping will be a powerful tool to control undesired SBS in ICF applications.

Notes and References

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